

Hyperbolic configurations of roots and Hecke algebras

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Abstract

This paper deals with infinite Coxeter groups. We use geometric techniques to prove two main results. One is of Lie-theoretic nature; it shows the existence of many hyperbolic configurations of three pairwise disjoint roots in a given Coxeter complex, provided it is not a Euclidean tiling. The other is both of algebraic and measure-theoretic nature since it deals with Hecke algebras; it shows that for automorphism groups of buildings, convolution algebras of bi-invariant functions are never commutative, provided the building is not Euclidean. Proofs are of geometric nature: the main idea is to exhibit and use enough trees of valency ≥ 3 inside a non-affine Coxeter complex.

Keywords: Coxeter groups; Buildings; Hecke algebras.

Introduction

Finite and affine Coxeter groups have been known and understood for a long time: they are classified [Bou07]. Given the classification of finite Coxeter groups, the structure of the affine ones is quite simple: such a group is an extension of a finite Coxeter group by an abelian translation subgroup. On the other hand, the structure of general Coxeter groups remains mysterious, and less understood (see [Kra09] though, where many basic group-theoretic problems are nicely solved for arbitrary Coxeter groups); it is still by now an active domain of research.

Infinite non-affine Coxeter groups. There is an obvious dichotomy between finite and infinite Coxeter groups. In this paper we are only interested in infinite ones. In the study of the latter groups, a further sharp dichotomy has recently proven to be very useful, namely the distinction between affine and non-affine Coxeter groups. This difference concerning Coxeter groups has implied many other sharp alternatives concerning automorphism groups of buildings (recall that the Weyl group of a building, which reflects the shape of its apartments, is a Coxeter group). Indeed, for such an automorphism group G , the affineness of the Weyl group determines the possibility or not to see G as a matrix group [CR09], the existence or not of non-obvious quasi-characters in the sense of Gromov for G (via techniques of bounded cohomology) [CF09]; and in the present paper, the existence or not of a Gelfand pair for G .

The original result in this spirit is the so-called “strong Tits alternative” for Coxeter groups [MV00, NV02], which is both a model and a source of inspiration for the techniques of proofs:

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Theorem. *Let W be an irreducible Coxeter group and Γ a subgroup of W . Then either Γ is virtually abelian, or Γ virtually surjects onto a non-abelian free group.*

In particular, when $\Gamma = W$, we see that a non-affine Coxeter group virtually surjects onto a non-abelian free group. The main tool to prove this is the existence of embeddings of thick trees in the Coxeter complex. In this paper we prove that, conversely, there are enough such trees to embed equivariantly the Coxeter complex itself in a suitable product of trees.

Hyperbolic configuration of roots. The first series of results in this paper is relevant to Lie theory, and more precisely to root systems of arbitrary Coxeter groups. In the following, we have a combinatorial point of view on roots: we see them as half-apartments, as in [Tit87]. We first provide a geometric proof of the existence of many triples of pairwise disjoint roots in a non-affine infinite Coxeter complex. We also disprove the existence of any non-trivial normal amenable subgroup of a non-affine Coxeter group. More precisely, the first result is the following.

Theorem (See Theorem 2.3). *Let W be an infinite irreducible, non-affine Coxeter group. Then for every root α , there exists two roots β and γ such that α , β and γ are pairwise disjoint.*

This theorem —actually a slightly stronger version of it— was initially proved in [CR09, Theorem 14] by combinatorial arguments. Its main interest is that it rules out finite quotients for non-affine twin building lattices. This non-existence of finite index normal subgroup is the second half of the proof of simplicity of such lattices, so that it turns out that, for twin building lattices, non-linearity and simplicity are more or less equivalent.

The search for a geometric proof of this statement led us to use the recently defined “combinatorial compactification” [CL09], which parametrizes amenable subgroups in automorphism groups of buildings: up to finite index, such a subgroup fixes a point in the combinatorial compactification. In return, we get the following non-existence statement:

Proposition (See Corollary 2.4). *Let W be an infinite irreducible, non-affine Coxeter group. Then there is no non-trivial amenable normal subgroup of W .*

Note finally that by the strong Tits alternative, amenable subgroups of W are virtually abelian, and abelian subgroups of Coxeter groups were thoroughly studied in [Kra09, Section 6.8]. Indeed, D. Krammer proved in particular that if W contains some free abelian subgroup of rank $n \geq 2$, then this subgroup is contained in a parabolic subgroup of W which is either affine or reducible. Combined with our result, this provides a fairly complete understanding of infinite amenable subgroups of Coxeter groups.

Hecke and convolution algebras. The second part of this paper is devoted to another application of the existence of a hyperbolic configuration of roots, namely the study of convolution algebras. Let G be a group acting transitively enough (technically: strongly transitively, see Section 3.1) on a locally finite building, and let U be a compact open subgroup of G (typically: a facet stabilizer). We denote by $\mathcal{L}(G, U)$ the space of \mathbb{C} -valued bi- U -invariant functions with compact support. The vector space $\mathcal{L}(G, U)$ has a natural basis consisting of characteristic functions of classes in $U \backslash G / U$. When equipped with the convolution product, which we denote by $*$, the space $\mathcal{L}(G, U)$ becomes an associative \mathbb{C} -algebra which, by analogy with well-known classical cases, we call *Hecke algebra* (with respect to U). Several choices of compact open subgroups U are particularly relevant.

The first choice is when U is equal to the stabilizer, say \mathcal{B} , of a given chamber of X . Then, by a well-known argument [Bou07, IV.2, Exercises 22 to 24], the convolution algebra $\mathcal{L}(G, \mathcal{B})$ is isomorphic to a deformation of the group algebra $\mathbb{C}[W]$. This algebra

admits an algebraic presentation whose parameters can be made completely explicit by means of thicknesses of codimension 1 simplices in the building (called *panels*). In the classical case when G is an algebraic p -adic semisimple group acting on its Bruhat-Tits building X , a fundamental paper of A. Borel [Bor76] uses the Hecke algebra $\mathcal{L}(G, \mathcal{B})$ in order to reduce the study of some representations of G to an algebraic category of representations of $\mathcal{L}(G, \mathcal{B})$.

The second choice is when U is equal to some maximal compact subgroup, say K , that is the stabilizer of some vertex of X . When $(\mathcal{L}(G, K), *)$ is commutative, the couple (G, K) is called a *Gelfand pair*. The existence of a Gelfand pair in a locally compact group G is again of fundamental interest for the study of (spherical unitary) representations of G and for the existence of a Plancherel formula on G . When G is a real semi-simple Lie group, then for any maximal compact subgroup K , the pair (G, K) is a Gelfand pair, and when G is a p -adic Lie group, it is also true for some well-chosen maximal compact subgroups of G [Sat63, Mac71], called *special* subgroups [BT72, 4.4.9]. The proof of the existence of such special subgroups crucially uses the geometry of X . In contrast, we prove the following complementary statement, which confirms the dichotomy between affine and non-affine Coxeter groups:

Theorem (See Theorem 3.4). *Let X be a non-affine building and G be a closed, strongly transitive type-preserving subgroup of the group of automorphisms of X . Then, for any maximal compact subgroup K of G , the convolution algebra $(\mathcal{L}(G, K), *)$ of continuous bi- K -invariant functions with compact support on G is non-commutative.*

In the quite specific case when the building is right-angled Fuchsian (namely, apartments are tessellations of the Poincaré disk by regular right-angled polygons), the above result was proved by U. Bader and Y. Shalom [BS06, Section 5]. They disprove a well-known consequence of the existence of Gelfand pair on unitary representations. Our proof is constructive: we exhibit explicit functions which do not commute for the convolution. Note also that there exist affine buildings of dimension 2 giving rise to Gelfand pairs which are not associated to algebraic groups [Par06], so the existence of a Gelfand pair does not depend on the algebraic nature of the group, but really of the geometry of the building.

The arguments of the previous parts of this introduction, based of the strong Tits alternative, provide a good intuition for the proof of the above theorem. Namely, $\mathcal{L}(G, K)$ is a sub-vector space of $\mathcal{L}(G, \mathcal{B})$; a canonical basis is given by characteristic functions of classes in $K \backslash G / K$, and each of these functions is a finite sum of characteristic functions in the canonical basis of classes in $\mathcal{L}(G, \mathcal{B})$. Recall that when X is affine, the Weyl group W is virtually abelian, the non-commutative part of W being given by the linear part of W . This linear part, which is the spherical Weyl group, indexes the double classes mod \mathcal{B} whose union provides the suitable maximal compact subgroup K . At the level of characteristic functions, this corresponds to making sums of double classes mod \mathcal{B} , and the restriction of the convolution product $*$ is commutative because the non-commutative part of W is so to speak absorbed in these finite unions. Conversely, for the same reason we were led to expect the non-existence of any Gelfand pair in the non affine case, because by the strong Tits alternative it is precisely the case when W is far from being virtually abelian. Intuitively, it is impossible to get a commutative subalgebra of $\mathcal{L}(G, \mathcal{B})$ by taking suitable finite sums of characteristic functions.

We finally mention that there does exist a wide family of topologically simple, locally pro- p groups acting on non-affine buildings (and some other groups with even more general profinite facet stabilizers) [RR06]. These groups are provided by Kac-Moody, and even more general twin buildings. The analogy with algebraic groups over local fields suggest that they deserve to be studied from the point of view of harmonic analysis and unitary representations (see also the end of Section 3). The point of view of group cohomology linked to unitary representations has been initiated in [DJ02], generalizing to arbitrary building automorphism groups classical results due to A. Borel and N. Wallach [BW80].

Structure of the paper. The first two sections of the paper are devoted to the proof of Theorem 2.3. The first one explains how to embed a Coxeter complex into a product of trees. The second one uses this embedding to actually prove the theorem. The third section explains how one can deduce from it the non-commutativity of convolution algebras.

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1 Trees in Coxeter complexes

In this section, we explain how to construct trees in a general Coxeter complex, by techniques of dual trees which come from hyperbolic geometry. We prove that there are enough such trees to fully encode the Coxeter complex. The ideas that are presented here also appear in [DJ99], in [NV02].

1.1 Construction of the trees

Let (W, S) be a Coxeter system, with S finite. Let Σ be the associated Coxeter complex [AB08, Chapter 3]. The complex Σ has a geometric realization, called its Davis-Moussong realization. This construction is described in details for example in [Dav08] or in [AB08, 12.3]. In this realization, the chambers are replaced by copies of some suitable compact, piecewise Euclidean, metric spaces. We denote this geometric realization by $|\Sigma|$. It is a locally compact CAT(0) metric space. A *wall* in Σ is a convex subspace of $|\Sigma|$ which divides $|\Sigma|$ into two connected components. Recall also that a *root* is a half-space, *i.e.* a connected component of $|\Sigma|$ deprived of a wall. Combinatorially, it can be defined as a conjugate of a simple root $\alpha_s := \{w \in W \mid \ell(sw) > \ell(w)\}$ (where ℓ is the length of an element of W with respect to the canonical system of generators S).

Example 1.1. Let W be the free product of r copies of $\mathbb{Z}/2\mathbb{Z}$. Then the Davis-Moussong realization $|\Sigma|$ of the associated Coxeter complex is a regular tree of valency r . A chamber in $|\Sigma|$ is a *star*, namely the union of a vertex and the r half-edges adjacent to this vertex. A wall in $|\Sigma|$ is the middle of an edge. Thus the set of chambers of $|\Sigma|$ can be identified to the set of vertices, and the set of walls to the set of edges. A root is a connected component of the tree, deprived of the middle of an edge.

Since we know that there is an injection from W to some $\mathrm{GL}_n(\mathbb{C})$ [Bou07, V. 4.4], Selberg's lemma [Alp87] allows us to find a normal torsion-free finite index subgroup W_0 of W . We will now see that the orbits of walls in $|\Sigma|$ can be identified to some trees. This remark has already been done in [NV02] or [DJ99]. The following lemma is well-known. A proof can be found in [Mil76] or [NV02, Lemma 3.3]:

Lemma 1.2. *Let $g \in W_0$, and let H be a wall of $|\Sigma|$, of associated reflection r . Then either $gH = H$, or $gH \cap H = \emptyset$. In the first case, r and g commute.*

□

Consequently, the walls of the W_0 -orbit of some given wall H have pairwise empty intersection. They divide $|\Sigma|$ into connected components. Let us consider the graph $T_{W_0}(H)$ whose vertices are these components, which are linked by an edge if they are adjacent. Thus a wall in the W_0 -orbit of H is represented by an edge of $T_{W_0}(H)$.

It is clear that $T_{W_0}(H)$ is connected. Furthermore, removing an edge to $T_{W_0}(H)$ corresponds to removing a wall in $|\Sigma|$, and it turns it into a non-connected space; as the different walls in $W_0.H$ do not intersect, $T_{W_0}(H)$ is also divided into two connected components. Thus $T_{W_0}(H)$ is a tree. Note that this tree need not be locally finite. The

tree $T_{W_0}(H)$ is, in other words, the dual tree of the tessellation of $|\Sigma|$ given by the walls wH , with $w \in W_0$.

By construction, W_0 acts transitively on the edges of the tree. Furthermore, since W_0 is normal in W , one can define a simplicial action of W on the set of trees $T_{W_0}(H)$, with W_0 fixed. This action is defined by $w.T_{W_0}(H) = T_{W_0}(wH)$. Indeed, for all $g \in W_0$, there exists $g' \in W_0$ such that $wgH = g'wH$.

Furthermore, since W_0 is of finite index in W , and there is a finite number of W -orbits of walls, the W_0 -orbits of walls are also finite in number. Thus, there exists a finite number of walls H_1, \dots, H_l , such that each wall of Σ appears as an edge in exactly one of the $T_{W_0}(H_i)$, for each $1 \leq i \leq l$. Let us set $T_i = T_{W_0}(H_i)$.

1.2 Embedding of the Coxeter complex

In the preceding section, we defined a finite number of trees T_i , with $1 \leq i \leq l$. We also have seen that W_0 acts on each of these trees, and that W acts on this set of trees by permuting them. More precisely, let $w \in W$. The image by w of a wall in Σ is another wall in Σ , and thus the image of some edge in some T_i will be an edge in some $T_{\sigma(i)}$, for some permutation σ associated to w . Furthermore, if two edges are adjacent in T_i , then their images will be again adjacent in T_j . So, from the action on the set of edges we get an action on the set of vertices on $T_1 \cup \dots \cup T_l$. We define the action of W on $T_1 \times \dots \times T_l$ to be the diagonal action.

Let r_i be the valency of the homogeneous tree T_i . Note that r_i can be any integer, and can also be infinite (though countable). Still, it can not be equal to 1: this would mean that W_0 stabilizes a wall, which is impossible since it is infinite. We know that T_i can be seen as the (Davis-Moussong realization) of the Coxeter group $W^{r_i} \simeq (\mathbb{Z}/2\mathbb{Z})^{*r_i}$. This allows us to speak of roots in T_i .

Using the arguments above, we can prove:

Proposition 1.3. *Let W be a Coxeter group and Σ its Coxeter complex. Then there exists a W -equivariant embedding*

$$\psi : \Sigma \rightarrow T_1 \times \dots \times T_l.$$

Proof. Let x be a chamber in Σ and H a wall in Σ . Since x does not intersect any wall in the geometric realization $|\Sigma|$, it is contained in a unique connected component of $|\Sigma| \setminus W_0.H$. So we can associate to x a unique vertex of $T_{W_0}(H)$. Thus, we get a map ψ_H from the set of chambers of Σ to the set of vertices of $T_{W_0}(H)$.

Let e_H be the edge of $T_{W_0}(H)$ which corresponds to the wall H , and let σ be a panel contained in H . We use the notion of *projection* of a chamber C on a panel τ : this projection, denoted proj_τ , is defined to be the unique chamber adjacent to τ at minimal distance of x . If $\text{proj}_\sigma(x)$ is equal to some chamber C , then we have $\text{proj}_{e_H}(\psi_H(x)) = \psi_H(C)$. In particular, if α is a root of Σ with boundary wall H , then $\psi_H(\alpha)$ is a root of $T_{W_0}(H)$. Of course it is the same for any wall in the same W_0 -orbit.

For each wall H_1, \dots, H_l , we get some maps $\psi_{H_1}, \dots, \psi_{H_l}$. Their product is a map $\psi : \Sigma \rightarrow T_1 \times \dots \times T_l$, and we have to show that it is injective. Let $x, y \in \Sigma$ such that $\psi(x) = \psi(y)$. By considering the position of $\psi(x)$ and $\psi(y)$ in T_1 , we can see that, if α is a root of Σ whose boundary wall is in the W_0 -orbit of H_1 , then $x \in \alpha$ if and only if $y \in \alpha$. The same argument in each T_i proves that this is valid for every root of Σ . Hence the set of root containing x is equal to the set of roots containing y . This implies that $x = y$ (indeed, x is the unique chamber in the intersection of the root containing x with boundary walls adjacent to x).

Now, we have to prove that ψ is equivariant. Let $x \in \Sigma$ and $w \in W$. Let $(x_1, \dots, x_l) = \psi(x)$ and $(y_1, \dots, y_l) = \psi(w.x)$. Then $\psi(w.x)$ is uniquely determined by the roots in each tree containing $w.x$. These roots correspond to roots in Σ containing $w.x$, *i.e.* to

$\Phi(w.x) = w.\Phi(x)$. By definition of the action, $w\psi(x)$ is the unique point in $T_1 \times \cdots \times T_l$ which is contained in every root in each T_i which corresponds to a root in $w.\Phi(x)$. So, we have $\psi(w.x) = w.\psi(x)$, and ψ is equivariant. \square

1.3 Combinatorial compactification

We refer to [CL09] for the definition and basic facts about the combinatorial compactification. We will use the compactification $\mathcal{C}_1(\Sigma)$, which is a compactification of the set of chambers $\text{ch}(\Sigma)$.

In the case of a Coxeter group, this compactification can be defined in a simple way. Namely, if C is a chamber, then C is uniquely determined by the roots which contain C . Let Φ be the set of roots of Σ . This defines an injection $i : \text{ch}(\Sigma) \rightarrow 2^\Phi$. The target space is equipped with the product topology, hence is compact. We define $\mathcal{C}_1(\Sigma)$ to be the closure of $i(\text{ch}(\Sigma))$ in 2^Φ .

The combinatorial compactification of a tree is its usual compactification $\mathcal{C}_1(T) = T \cup \partial_\infty T$. The combinatorial compactification of a product of trees is then the product of their combinatorial compactifications: $\mathcal{C}_1(T_1 \times \cdots \times T_l) = \mathcal{C}_1(T_1) \times \cdots \times \mathcal{C}_1(T_l)$. Then, if Σ is any Coxeter complex, it can be embedded as above in a product of trees $T_1 \times \cdots \times T_l$. The same proof as in Proposition 1.3 shows that the combinatorial compactification of Σ is then the closure of Σ in $\mathcal{C}_1(T_1 \times \cdots \times T_l)$.

A useful fact about this compactification is that it behaves well with respect to amenable subgroups of W . Namely, we have the following [CL09, Theorem 6.1]:

Theorem 1.4. *An amenable subgroup of W virtually fixes a point in the combinatorial compactification $\mathcal{C}_1(\Sigma)$ of W .*

Proof. The precise statement of [CL09, Theorem 6.1] is that an amenable subgroup of W virtually fixes a point in the compactification $\mathcal{C}_{\text{sph}}(\Sigma)$ of spherical residues of Σ , which is larger than $\mathcal{C}_1(\Sigma)$. This compactification is defined in [CL09, Definition 2.1]. This means that this amenable subgroup fixes a spherical residue in some apartment Σ_ξ of the stratification defined in [CL09, Theorem 5.5]. But, by definition, spherical residues in apartments are finite, so this amenable subgroup virtually fixes a chamber in Σ_ξ . These chambers are exactly the points of $\mathcal{C}_1(\Sigma)$. \square

2 Consequences of the strong Tits alternative

In this section, we prove the existence of many hyperbolic configurations of roots in non-affine Coxeter groups. The key arguments are relevant to the geometric proof of the strong Tits alternative.

2.1 Existence of pairwise disjoint roots

The classical Tits alternative asserts that any finitely generated linear group either is virtually solvable or contains a non-abelian free group [Tit72]. We say that a class of groups satisfies the strong Tits alternative if any group in this class either is virtually abelian or virtually surjects onto a non-abelian free group. One of the main theorems of [MV00] is that Coxeter groups satisfy this strong Tits alternative. Later on, in [NV02], it was proved that subgroups of Coxeter groups also satisfy the strong Tits alternative. The strategy used in the latter is to give an interpretation of this fact in terms of the trees described above. More precisely, they prove the following:

Proposition 2.1. *Let W be an infinite Coxeter group. Let W_0 be as above. If every tree $T_{W_0}(H)$ is a line, then W_0 (and hence W) is virtually abelian.*

□

Combined with the strong Tits alternative for the Coxeter group W , this yields the following:

Proposition 2.2. *In any infinite, non affine Coxeter group, there exists three roots which are pairwise disjoint.*

Proof. Let W_0 be as above. Since W is not affine, it is not virtually abelian by the strong Tits alternative. So there is some wall H for which $T_{W_0}(H)$ is not a line, and therefore is regular of valency greater or equal to 3. Thus there are three roots in $T_{W_0}(H)$ that are pairwise disjoint, and these roots are the image by ψ of three disjoint roots of W . □

2.2 Uniformness

Our goal is to prove that the above proposition on the existence of pairwise disjoint roots can be refined, under an assumption of irreducibility, in order to prove that one of these three roots may be chosen arbitrarily.

Theorem 2.3. *Let W be an infinite, irreducible, non affine Coxeter group. Let α be a root in W . Then there exists two roots β and γ which are disjoint and also disjoint from α .*

Proof. Let W_0 be a normal, torsion-free, finite index subgroup of W . Since every root of W appears as a root in some $T_{W_0}(H)$, we just have to prove that $T_{W_0}(H)$ can never be a line.

Let r be a reflection in W , and H its associated wall. If $w \in W$, then wrw^{-1} is a reflection with associated wall wH . As we have seen above, w sends the tree $T_{W_0}(H)$ onto $T_{W_0}(wH)$. So these two trees are isomorphic. Hence we only have to argue on conjugacy classes of reflections.

Let R be the set of all reflections of W , and let R' be the subset of R consisting of reflections whose associated wall H is such that $T_{W_0}(H)$ is a line. Let $R'' = R \setminus R'$. By a theorem of Deodhar [Deo89], we know that the groups W' generated by R' and W'' generated by R'' are Coxeter groups. Furthermore, the above argument proves that R' is closed under conjugations by elements of W , so that W' is normal in W . Similarly, W'' is normal in W . Note that, by Proposition 2.2, R'' is not empty, and hence $W'' \neq \{1\}$.

Recall the following theorem of L. Paris [Par07, Theorem 4.1]: an infinite, irreducible Coxeter group cannot be the product of two non-trivial subgroups. In view of this fact, we prove that W is the direct product of W' and W'' . Since $W'' \neq \{1\}$, this will prove that $W'' = W$, hence $R'' = R$. As W' and W'' are both normal, and altogether obviously generate W , what is left to show is that their intersection is trivial.

Let $A = W' \cap W''$. The group A is normal both in W' and W'' . We prove first that A is finite. If $W'_0 = W' \cup W_0$, then we see that for every wall H of W' , the tree $T_{W'_0}(H)$ is in fact a line. Hence, by Proposition 2.1, W' is an virtually abelian, and therefore is amenable.

Let T_1, \dots, T_l be the trees constructed in Section 1. Up to permutation, we can assume that the valency of T_1, \dots, T_k is greater or equal to 3, and that the valency of T_{k+1}, \dots, T_l is equal to 2. By construction, W'' stabilizes the product $T_1 \times \dots \times T_k$.

Furthermore, W'' contains all reflections with respect to the walls in these trees. So, if T is one of these trees and is of valency r , then W'' contains the free Coxeter group $(\mathbb{Z}/2\mathbb{Z})^{*r}$, acting on T in a natural way. Since this group is not amenable, it can not have any finite index subgroup fixing a point in ∂T . Therefore the orbits of $(\mathbb{Z}/2\mathbb{Z})^{*r}$, and hence of W'' acting on $\partial_\infty T$ are infinite.

Since A is amenable, it has a finite index subgroup that fixes a point in the combinatorial compactification $\mathcal{C}_1(\Sigma)$. Up to passing again to a subgroup of finite index, we can

assume that A really fixes this point, and furthermore that it stabilizes every tree T_i , for $i \leq k$. Let T be one of those trees. Since we know that A fixes a point in $\mathcal{C}_1(\Sigma)$, we know that A fixes a point in $T \cup \partial_\infty T$, denoted by ξ . Assume first that $\xi \in \partial_\infty T$. Now, for every $w \in W''$, wAw^{-1} fixes the point $w\xi$ in $\partial(wT)$. Since $\text{Stab}_{W''}(T)$ acting on ∂T has infinite orbits, this means that A fixes infinitely many points in ∂T . Since a hyperbolic translation in T only fixes two points, this means that the actions of A on T is only by elliptic elements. Obviously if $\xi \in T$, then A also acts on T by elliptic elements.

Furthermore, all the reflections of W'' are associated to reflections of one of the tree T_i , for $i \leq k$. Thus, in a similar way to Proposition 1.3, we see that W'' is equivariantly embedded in $T_1 \cdots \times \cdots T_k$. Since A acts via elliptic elements on each of these trees, the action of A on W'' has finite orbits. Hence, A is finite.

Thus we have proved that $W' \cap W''$ is finite. But this is a finite normal subgroup of W . By [Par07, Proposition 4.2], this implies that this subgroup is trivial. \square

Theorem 2.3 was proved by Caprace and Rémy with an application in mind: the study of non-affine Kac-Moody groups. These groups were constructed by Tits [Tit87]. In the affine case, Tits' construction leads to particular lattices in semi-simple Lie groups over local fields; in particular, they act on Euclidean buildings. The non-affine Kac-Moody groups act on non-Euclidean buildings, in which the geometry of non-affine Coxeter groups appear. Hence, it is not surprising to see that there are some qualitative differences between affine and non-affine Kac-Moody groups. Using Theorem 2.3, Caprace and Rémy prove that Kac-Moody groups over finite fields with an infinite, irreducible and non-affine Weyl group are simple (up to taking a finite-index quotient of a finite-index subgroup) [CR09, Theorem 19]. It is quite the opposite to lattices in semi-simple Lie groups over local fields, which are residually finite, as finitely generated linear groups.

Using both the proof and the result of Theorem 2.3, it is easy to deduce the following fact, which has an interest of its own:

Corollary 2.4. *An irreducible, non-affine Coxeter group has no non-trivial amenable subgroup.*

Proof. We have seen in the course of the proof that if all the trees $T_{W_0}(H)$ are of valency ≥ 3 , then a normal, amenable subgroup of W is in fact finite, hence trivial. By Theorem 2.3, it is the case of all irreducible, non-affine Coxeter group. \square

3 Non-commutativity of convolution algebras

In this section, we prove that Hecke algebras of groups acting on a non-Euclidean building, with respect to any maximal compact subgroup, can never be commutative. The proof consists first in translating the expression of the convolution product in geometric and combinatorial terms: we prove that the commutativity of the convolution product can be interpreted as an equality between some sets of chambers. Then we prove that this equality never holds in the non-affine case, which is in sharp contrast with harmonic analysis on Bruhat-Tits buildings [Mac71].

3.1 Notation and preliminaries on buildings

Let W be a Coxeter group and X be a locally finite building whose Weyl group is W . We denote the Davis realization of X , as defined in [Dav08], by $|X|$; it is a CAT(0) and complete metric space. We assume X is of finite thickness and denote δ the W -distance between chambers of X [AB08, Chapter 5]. Recall that the W -distance is a function $\delta : X \times X \rightarrow W$ which encodes the relative position of chambers. More precisely, it

can be defined as the element of W obtained by concatenation of the types of the panels crossed by a minimal gallery from one chamber to another.

If a is a chamber in X , the set of chambers c such that $\delta(a, c) = w$ is denoted by $\mathcal{C}_w(a)$.

We endow the group $\text{Aut}(X)$ of automorphisms of X with the compact open topology: it is the smallest topology which makes stabilizers of points in $|X|$ open; it is then easy to see that these stabilizers are also compact. Let G be a closed subgroup of $\text{Aut}(X)$. Recall that the action of G on X is said to be *strongly transitive* if it is transitive on the pairs of the form (C, A) , where C is a chamber included in an apartment A . We assume that G acts strongly transitively on X , and that G is type-preserving.

Let K be a maximal compact subgroup of G . By a well-known fixed-point lemma [BH99, Corollary 2.8], we know that K is the stabilizer of some vertex o of $|X|$. By transitivity of the action of G , the quotient G/K can be identified with the set of vertices in X of the same type as o . Let W_o be the stabilizer of o in W . It is a maximal spherical subgroup of W . Let \mathbb{A} be an apartment of X containing o .

Since X is locally finite, G is locally compact, and therefore endowed with a Haar measure dg . We assume that dg is normalised so that $\text{Vol}(K, dg) = 1$, which is possible because K is compact and open.

Let $\mathcal{L}(G, K)$ be the space of continuous compactly supported functions from G to \mathbb{C} which are bi- K -invariant, that is, such that

$$\forall k, k' \in K \forall g \in G \quad f(kgk') = f(g).$$

It is a vector space over \mathbb{C} , a basis of which being the set of characteristic functions of classes in $K \backslash G / K$. The convolution product

$$(f * f')(g) = \int_G f(gh)f'(h^{-1})dh = \int_G f(h)f'(h^{-1}g)dh$$

turns it into an algebra. We call it the *Hecke algebra* of G with respect to K .

In the classical context, where \mathbb{G} is a semisimple algebraic group over a local field k , the topological group G is the group of k -rational points $\mathbb{G}(k)$, and X is the Bruhat-Tits building of \mathbb{G} over k . The algebra $\mathcal{L}(G, K)$ is then a basic object of study for the spherical harmonic analysis of G [Sat63, Mac71].

Functions in $\mathcal{L}(G, K)$ can also be thought of as functions on G/K which are left-invariant. Therefore, we can see them as functions on the set of vertices of the same type as o , which are constant on any K -orbit of vertices.

Let $x \in G$ and $\lambda \in G$. We set $V_\lambda(x) = xK\lambda K$. It is clear that $V_\lambda(x)$ only depends on the class of λ in $K \backslash G / K$ and on the class of x in G/K ; hence, it makes sense to write $V_\mu(y)$ when μ and y are two vertices of the same type as o in the building. Furthermore, since $V_\lambda(x)$ is invariant by right-multiplication by an element of K , the set $V_\lambda(x)$ can be seen as a set of vertices in the building X . Geometrically, $V_\lambda(x)$ should be thought of as a kind of sphere in X centred at x and of “radius” λ . When $x = o$, it is exactly the K -orbit of λ in X . Note that $y \in V_\lambda(x)$ if and only if $x \in V_{\lambda^{-1}}(y)$.

Since the action of G is strongly transitive, for every $\lambda \in G/K$, there is always a μ in the apartment \mathbb{A} such that $V_\lambda(x) = V_\mu(x)$. Note that a vertex in \mathbb{A} of the same type as o can also be thought of as an element of W/W_o . Thus, it also makes sense to write $V_\lambda(x)$, when λ and x are element of W/W_o , or even elements of W .

At last, a root α is understood to be a half-space in some apartment A . Its boundary wall is denoted by $\partial\alpha$. The *star* of a vertex x is defined as the set of chambers whose boundary contains x . It is denoted by $\text{st}(x)$.

3.2 Geometric expression of the convolution product

This section is devoted to translate the expression of the convolution product into a geometric counting.

Lemma 3.1. *Let $\lambda, \mu \in G$. Let f and g be the characteristic functions of $K\lambda K$ and $K\mu K$, respectively. Then, for all $x \in G/K$, we have:*

$$(f * g)(x) = |V_\lambda(0) \cap V_{\mu^{-1}}(x)|.$$

Proof. Since K is compact and open in G , the quotient space G/K is discrete, so that the G -invariant measure on G/K is the counting measure. Hence we get

$$(f * g)(x) = \int_G f(h)g(h^{-1}x)dh = \sum_{h \in G/K} \int_K f(hk)g(k^{-1}h^{-1}x)dk.$$

Since f and g are bi- K -invariant, using that dg is normalised so that $\text{Vol}(K, dg) = 1$, we deduce that $(f * g)(x) = \sum_{h \in G/K} f(h)g(h^{-1}x)$. Finally, we have:

$$\begin{aligned} (f * g)(x) &= \sum_{h \in G/K} f(h)g(h^{-1}x) \\ &= |V_\lambda(o) \cap \{h \in G/K \mid h^{-1}x \in K\bar{\mu}K\}| \\ &= |V_\lambda(o) \cap V_{\mu^{-1}}(x)|, \end{aligned}$$

which concludes the proof. \square

Thus, checking the commutativity of $\mathcal{L}(G, K)$ amounts to checking whether, for all $\lambda, \mu \in G$, we have $|V_\lambda(o) \cap V_{\mu^{-1}}(x)| = |V_\mu(o) \cap V_{\lambda^{-1}}(x)|$.

To calculate this quantity, we will rather do the calculation on chambers instead of vertices: it is more adapted to the point of view of buildings as W -metric spaces [AB08, Chapter 5]. Let N be the number of chambers in the star of o . By transitivity of the action of G , the integer N is also the number of chambers in the star of any vertex $x \in G/K$. Recall that, for a chamber a in X and $w \in W$, we write $\mathcal{C}_w(a)$ for the set of chambers c such that $\delta(a, c) = w$.

Lemma 3.2. *For all $x \in G/K$, and for all $\lambda, \mu \in W$, we have*

$$|V_\lambda(o) \cap V_{\mu^{-1}}(x)| \leq \frac{1}{N} \sum_{a \in \text{st}(o), b \in \text{st}(x)} \sum_{w_1 \in \lambda W_o} \sum_{w_2 \in \mu^{-1} W_o} |\mathcal{C}_{w_1}(a) \cap \mathcal{C}_{w_2}(b)|.$$

Proof. Let π be the map which associates to a chamber of X its only adjacent vertex which is of the same type as o . Then for any $y \in G/K$, the preimage $\pi^{-1}(y)$ is equal to $\text{st}(y)$. In particular, $\pi^{-1}(y)$ is of cardinality N . Therefore, we have the equality:

$$N|V_\lambda(o) \cap V_{\mu^{-1}}(x)| = |\pi^{-1}(V_\lambda(o) \cap V_{\mu^{-1}}(x))|.$$

Let us choose a chamber C whose closure contains o . The set of chambers a such that $\pi(a) = o$ is equal to $\text{st}(o)$. It is also the set of chambers whose W -distance to C is in W_o . Likewise, the chambers of \mathbb{A} containing $\lambda.o$ are the chambers of \mathbb{A} whose W -distance to C lies in λW_o . Chambers c containing a vertex in $V_\lambda(o)$ are then K -transforms of these ones: there exists $g \in K$ such that $\pi(gc) = \lambda.o$. Letting $a = g^{-1}C$, we see that $\delta(a, c) = \delta(ga, gc) = \delta(C, gc) \in \lambda W_o$. Therefore, if a chamber c contains a vertex in $V_\lambda(o)$, then there exists a chamber a containing o and there exists also $w_1 \in \lambda W_o$ such that $c \in \mathcal{C}_{w_1}(a)$.

Furthermore, for any $a \in \text{st}(o)$ and $w_1 \in \lambda W_o$, using the strong transitivity of the action of G , any chamber $c \in \mathcal{C}_{w_1}(a)$ is a K -transform of a chamber in \mathbb{A} such that $\delta(a, c) \in \lambda W_o$, thus is such that $\pi(c) \in V_\lambda(o)$. Therefore, we have:

$$\pi^{-1}(V_\lambda(o)) = \bigcup_{a \in \text{st}(o)} \bigcup_{w_1 \in \lambda W_o} \mathcal{C}_{w_1}(a). \quad (*)$$

Applying (*) with o replaced by x and λ replaced by μ^{-1} , we see that:

$$\pi^{-1}(V_{\mu^{-1}}(x)) = \bigcup_{b \in \text{st}(x)} \bigcup_{w_2 \in \mu^{-1}W_o} \mathcal{C}_{w_2}(b).$$

Consequently, we have

$$\pi^{-1}(V_\lambda(o) \cap V_{\mu^{-1}}(x)) = \bigcup_{a \in \text{st}(o), b \in \text{st}(x)} \bigcup_{w_1 \in \lambda W_o} \bigcup_{w_2 \in \mu^{-1}W_o} \mathcal{C}_{w_1}(a) \cap \mathcal{C}_{w_2}(b),$$

which, taking cardinality, proves the lemma. \square

3.3 Non-commutativity in the non-affine case

We assume hereafter that W is infinite and non-affine. We prove the non commutativity of $\mathcal{L}(G, K)$. To do this, we will find λ, μ and x , chosen in W , such that $|V_\lambda(o) \cap V_{\mu^{-1}}(x)| = 0$ whereas $|V_\mu(o) \cap V_{\lambda^{-1}}(x)| \neq 0$.

Let us take $\mu = x\lambda^{-1}$. Then $V_\mu(o) \cap V_{\lambda^{-1}}(x)$ contains $\mu.o$, and therefore is not empty. Our goal is thus to find x and λ such that $V_\lambda(o) \cap V_{x\lambda^{-1}}(x)$ is empty.

Using Lemma 3.2, we have to find x and λ such that for all chambers a and b containing o and x respectively, and for all $w_1 \in \lambda W_o$ and $w_2 \in \mu^{-1}W_o$, we have $\mathcal{C}_{w_1}(a) \cap \mathcal{C}_{w_2}(b) = \emptyset$. To do this, we must give an estimate of the W -distance between a and b . We will in fact choose a reflection for λ .

Lemma 3.3. *Let $s \in W$ be a reflection. Let a and b be two chambers. Let $\mu \in W$. Assume there exists $w_1 \in sW_o$ and $w_2 \in \mu^{-1}W_o$ such that $\mathcal{C}_{w_1}(a) \cap \mathcal{C}_{w_2}(b) \neq \emptyset$. Then the W -distance between a and b belongs to $W_o\mu \cup sW_o\mu$.*

Proof. As a preliminary remark, let us note that, since G acts strongly transitively on X , it is transitive on the set of couples of chambers with the same W -distance [AB08, Corollary 6.12]. Thus, $|\mathcal{C}_{w_1}(a) \cap \mathcal{C}_{w_2}(b)|$ does not depend on a and b , but only on the W -distance between a and b . Therefore, we can assume that $b \in \mu \text{st}(o)$.

Let $c \in \mathcal{C}_{w_1}(a) \cap \mathcal{C}_{w_2}(b)$. Because of the choice we made on b , we remark that

$$\text{st}(o) = \bigcup_{w \in \mu^{-1}W_o} \mathcal{C}_w(b).$$

Consequently, $c \in \text{st}(o)$. Furthermore, $\delta(a, c) = sw_0 \in sW_o$. Hence there exists a minimal gallery of type sw_0 from a to c , with $w_0 \in W_o$. This gallery is obtained by the concatenation of a gallery of type s from a to some chamber, say c_0 , and a gallery of type w_0 from c_0 to c . Thus, we get that $\delta(c_0, c) = w_0 \in W_o$ and therefore $c_0 \in \text{st}(o)$, so that $c_0 \in \mathcal{C}_w(b)$ for some $w \in \mu^{-1}W_o$.

Thus, we have $\delta(a, c_0) = s$ and $\delta(c_0, b) \in W_o\mu$. By definition of the W -distance [AB08, Definition 5.1], this implies that $\delta(a, b) \in W_o\mu \cup sW_o\mu$. \square

We can now conclude:

Theorem 3.4. *Let X be a locally finite building and G a closed subgroup of $\text{Aut}(X)$. Assume that G acts strongly transitively on X . Let K be the stabilizer in G of a vertex o in X . Then the convolution algebra $\mathcal{L}(G, K)$ is not commutative.*

Proof. Let $x \in W$ and s be a reflection in W . Let a be a chamber containing o and b a chamber containing x . The W -distance $\delta(a, b)$ belongs to xW_o . Let $\mu = xs$, so that $V_\mu(o) \cap V_s(x)$ contains $\mu.o$.

As explained in the beginning of the section, and using Lemma 3.2, we disprove the commutativity of $\mathcal{L}(G, K)$ if we choose s and x such that for any $a \in \text{st}(o)$ and $b \in \text{st}(x)$, for any $w_1 \in sW_o$ and $w_2 \in sx^{-1}W_o$, we have $\mathcal{C}_{w_1}(a) \cap \mathcal{C}_{w_2}(b) = \emptyset$. By Lemma 3.3, this implies that for such a and b we have $\delta(a, b) \in W_oxs \cup sW_oxs$. Since $a \in \text{st}(o)$ and $b \in \text{st}(x)$, we have furthermore $\delta(a, b) \in xW_o$. Hence, we will prove that $\mathcal{L}(G, K)$ is not commutative if we prove that there exist $x \in W$ and a reflection s such that $W_oxs \cap xW_o = \emptyset$ and $sW_oxs \cap xW_o = \emptyset$.

Assume that $\mathcal{L}(G, K)$ is commutative. It implies that for all x and s one of these intersections is not empty. The idea is to choose x and s , using Proposition 2.2, in order to get a contradiction.

By this proposition, there exist three roots α, β and γ in \mathbb{A} whose pairwise intersections are empty. Let W' be the subgroup of W generated by the reflections r_1, r_2 and r_3 with respect to $\partial\alpha, \partial\beta$ and $\partial\gamma$. As in Section 1, the walls of $W'.\partial\alpha$ define a dual tree T .

Let us define the map φ which associates to a vertex of T the corresponding connected component of $A - W'.\partial\alpha$. This map induces another map φ_∞ , going from $\partial_\infty T$ to the set of subsets of $\partial_\infty |\mathbb{A}|$ defined as follows: for $\xi \in \partial_\infty T$, the subset $\varphi_\infty(\xi)$ is the set of limits of sequences of elements $y_n \in \varphi(x_n)$ when (x_n) is a sequence of vertices of T which tends to ξ . Then we see that if $\xi \neq \xi'$ then $\varphi_\infty(\xi) \cap \varphi_\infty(\xi') = \emptyset$. Indeed, assume that there exists some point $\eta \in \varphi_\infty(\xi) \cap \varphi_\infty(\xi')$, this would mean that there exist two sequences (y_n) and (z_n) of points in $|\mathbb{A}|$ converging to η and such that $\lim_n \varphi^{-1}(y_n) = \xi$ and $\lim_n \varphi^{-1}(z_n) = \xi'$. This would mean that (y_n) and (z_n) stay at bounded distance, which implies that $\varphi^{-1}(y_n)$ and $\varphi^{-1}(z_n)$ stay at bounded distance. Hence $\xi = \xi'$.

Let $\tau \in W' \subset W$ be the product of two reflections across two distinct walls of $W'.\partial\alpha$. Since these two walls do not intersect each other, τ is a hyperbolic element of $\text{Aut}(\mathbb{A})$. It is also a hyperbolic element of $\text{Aut}(T)$. Thus, there exists $\xi_1 \in \partial_\infty T$ such that for all $y \in T$, we have $\lim_{n \rightarrow +\infty} \tau^n y = \xi_1$. Similarly, there exists $\eta \in \partial_\infty(|\mathbb{A}|)$ such that we have $\lim_{n \rightarrow +\infty} \tau^n z = \eta$ for every $z \in |\mathbb{A}|$. By definition, we have $\eta \in \varphi_\infty(\xi_1)$ (See Figure 1).

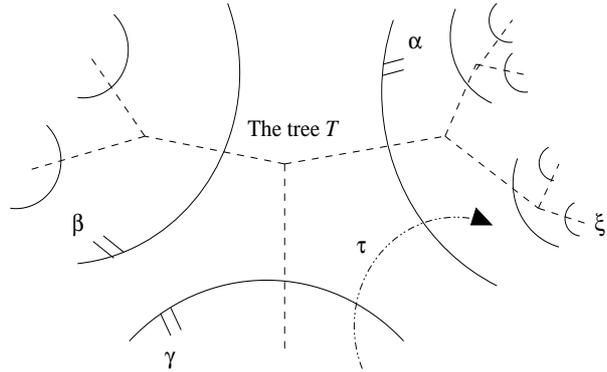


Figure 1: The tree T and the hyperbolic isometry τ

Since we assumed $\mathcal{L}(G, K)$ to be commutative, we know that for any reflection s and any $n \in \mathbb{N}$, one of the intersections $W_o\tau^{-n}s \cap \tau^{-n}W_o$ and $sW_o\tau^{-n}s \cap \tau^{-n}W_o$ is not empty. Since W_o is finite, this implies that there exists $g \in W_o$ such that either $\tau^{-n}g \in W_o\tau^{-n}s$ for an infinite number of n 's, or $\tau^{-n}g \in sW_o\tau^{-n}s$ for an infinite number of n 's. We extract a subsequence from $(\tau^{-n})_n$ such that one of these two cases occur for every n and

a fixed g . The first case means that $\tau^{-n}g\tau^n \in W_o$, hence $g\tau^n o = \tau^n o$. In the second case, we get $g\tau^n o = \tau^n s o$. Passing to the limit in the equalities above, we get in both cases $gs\eta = \eta$.

Therefore, η and $s\eta$ are in the same W_o -orbit. Thus, we will get the contradiction we want if we choose s such that this is not true. The idea is that the orbits of points in the boundary of \mathbb{A} contain a copy of orbits of the orbits of W' acting on the tree T , and therefore cannot be finite.

More precisely, let $\Xi = \{\xi_2 \in \partial_\infty T \mid \varphi_\infty(\xi_2) \cap W_o \eta \neq \emptyset\}$. Since W_o is finite, it is clear that this set is finite. But the set of $s\xi_1$, when s runs through the set of reflections in W' , is infinite. Consequently, there exists some $s_0 \in W'$ such that $s_0\xi_1 \notin \Xi$. This means that $gs_0\eta \notin \varphi_\infty(s_0\xi_1)$ for all $g \in W_o$, i.e. $gs_0\eta \notin s_0\varphi_\infty(\xi_1)$. Since η belongs to $\varphi_\infty(\xi_1)$, we have that $gs_0\eta \neq \eta$ for every $g \in W_o$, which is the expected contradiction, and proves the theorem. \square

Corollary 3.5. *With the same hypotheses, the group G has no Gelfand pair.*

Proof. Let K_0 be a compact subgroup of G . By the Bruhat-Tits fixed point lemma [BH99, Corollary 2.8], K_0 fixes a point in $|X|$, and therefore fixes a closed facet in X . Hence it fixes some vertex o , which means that it is contained in the stabilizer K of o . By Theorem 3.4, the algebra $\mathcal{L}(G, K)$ is not commutative. Since $\mathcal{L}(G, K)$ is a sub-algebra of $\mathcal{L}(G, K_0)$, this implies that $\mathcal{L}(G, K_0)$ is not commutative, hence (G, K_0) is not a Gelfand pair. \square

As previously mentioned, this theorem is proved in [BS06] for Fuchsian right-angled buildings. In fact, using a (suitable) tree in such a building, and considering its (self-normalized) stabilizer H , they obtain the unitary representation $\ell^2(G/H)$. This representation is irreducible because $H = N_G(H)$, but has infinitely many linearly independent K -fixed vectors, for any compact subgroup K . This prevents K from being a Gelfand subgroup of G . Moreover, since H is open, non-compact and of infinite index, the vanishing at infinity of matrix coefficients of unitary representations does not hold; this property, called *Howe-Moore property*, holds in the classical Euclidean case, and implies some mixing property for boundary actions.

General groups acting on buildings can also be exotic in another way, related to the Hecke algebra $\mathcal{L}(G, \mathcal{B})$. From an algebraic viewpoint, this algebra is completely understood: it has an explicit presentation, which depends on the Weyl group and on the thicknesses of the building [Bou07, IV.2, Exercises 22 to 24]. Namely, it is generated as a vector space by symbols a_w , with $w \in W$. The algebra structure is given by the relations $a_s \cdot a_w = (q_s - 1)a_w + q_s a_{sw}$ if $\ell(sw) < \ell(w)$, and $a_s a_w = a_{sw}$ if $\ell(sw) > \ell(w)$, where $1 + q_s$ is the thickness of panels of type $s \in S$. For algebraic groups over local fields, there are strong constraints on the parameters q_s , since they must be a power of the cardinality of the residue field. There are new examples of buildings with strongly transitive automorphism groups and for which any family of independent parameters $\{1 + q_s\}_{s \in S}$ can occur as family of thicknesses, provided q_s is a prime power or a prime power minus 1 [RR06].

To sum up, the Hecke-theoretic part of this paper brings a further element in the dichotomy between automorphism groups of Euclidean and non-Euclidean buildings (another one being the possibility to have simple lattices or not). Indeed, the previous theorems and examples show that, in order to develop harmonic analysis on sufficiently transitive automorphism groups of buildings, some new methods and ideas are required with respect to classical techniques such as Gelfand pairs, Hecke algebras, etc. Still, the analogy viewpoint on automorphism groups of buildings is already known to be fruitful and should be investigated further. For instance, J. Dymara and T. Januszkiewicz [DJ02] proved that many classical techniques and results, such as induction and relationship between continuous and discrete cohomology as developed in the book [BW80], hold for more general for automorphism groups of buildings. The latter work calls for a deeper investigation of the unitary representation theory of such groups.

References

- [AB08] Peter Abramenko and Kenneth S. Brown. *Buildings*, volume 248 of *Graduate Texts in Mathematics*. Springer, New York, 2008.
- [Alp87] Roger C. Alperin. An elementary account of Selberg’s lemma. *Enseign. Math.*, 33(3-4):269–273, 1987.
- [BH99] Martin R. Bridson and André Haefliger. *Metric spaces of non-positive curvature*, volume 319 of *Grundlehren der Mathematischen Wissenschaften*. Springer-Verlag, Berlin, 1999.
- [Bor76] Armand Borel. Admissible representations of a semi-simple group over a local field with vectors fixed under an Iwahori subgroup. *Invent. Math.*, 35:233–259, 1976.
- [Bou07] Nicolas Bourbaki. *Groupes et Algèbres de Lie. Chapitres 4–6. Éléments de Mathématique*. Springer-Verlag, Berlin, 2007.
- [BS06] Uri Bader and Yehuda Shalom. Factor and normal subgroup theorems for lattices in products of groups. *Invent. Math.*, 163:415–454, 2006.
- [BT72] François Bruhat and Jacques Tits. Groupes réductifs sur un corps local. *Inst. Hautes Études Sci. Publ. Math.*, (41):5–251, 1972.
- [BW80] Armand Borel and Nolan R. Wallach. *Continuous cohomology, discrete subgroups, and representations of reductive groups*, volume 94 of *Annals of Mathematics Studies*. Princeton University Press, Princeton, N.J., 1980.
- [CF09] Pierre-Emmanuel Caprace and Koji Fujiwara. Rank one isometries of buildings and quasi-morphisms of Kac-Moody groups. *Preprint*, 2009. Available at <http://arxiv.org/abs/0809.0470>.
- [CL09] Pierre-Emmanuel Caprace and Jean Lécureux. Combinatorial and group-theoretic compactifications of buildings. *Preprint*, 2009. Available at <http://arxiv.org/abs/0901.4188>.
- [CR09] Pierre-Emmanuel Caprace and Bertrand Rémy. Simplicity and superrigidity of twin buildings lattices. *Invent. Math.*, 176:169–221, 2009.
- [Dav08] Michael W. Davis. *The geometry and topology of Coxeter groups*, volume 32 of *London Mathematical Society Monographs Series*. Princeton University Press, Princeton, NJ, 2008.
- [Deo89] Vinay V. Deodhar. A note on subgroups generated by reflections in Coxeter groups. *Arch. Math. (Basel)*, 53(6):543–546, 1989.
- [DJ99] Alexander Dranishnikov and Tadeusz Januszkiewicz. Every Coxeter group acts amenably on a compact space. In *Proceedings of the 1999 Topology and Dynamics Conference (Salt Lake City, UT)*, volume 24, pages 135–141, 1999.
- [DJ02] Jan Dymara and Tadeusz Januszkiewicz. Cohomology of buildings and their automorphism groups. *Invent. Math.*, 150(3):579–627, 2002.
- [Kra09] Daan Krammer. The conjugacy problem for Coxeter groups. *Groups Geom. Dyn.*, 3(1):71–171, 2009.
- [Mac71] I. G. Macdonald. *Spherical functions on a group of p -adic type*. Ramanujan Institute, Centre for Advanced Study in Mathematics, University of Madras, Madras, 1971. Publications of the Ramanujan Institute, No. 2.
- [Mil76] John J. Millson. On the first Betti number of a constant negatively curved manifold. *Ann. of Math. (2)*, 104(2):235–247, 1976.
- [MV00] Gregori A. Margulis and Èrnest. B. Vinberg. Some linear groups virtually having a free quotient. *J. Lie Theory*, 10(1):171–180, 2000.

- [NV02] Guennadi A. Noskov and Èrnest B. Vinberg. Strong Tits alternative for subgroups of Coxeter groups. *J. Lie Theory*, 12(1):259–264, 2002.
- [Par06] James Parkinson. Buildings and Hecke algebras. *J. Algebra*, 297(1):1–49, 2006.
- [Par07] Luis Paris. Irreducible Coxeter groups. *Internat. J. Algebra Comput.*, 17(3):427–447, 2007.
- [RR06] Bertrand Rémy and Mark Ronan. Topological groups of Kac-Moody type, right-angled twinings and their lattices. *Comment. Math. Helv.*, 81(1):191–219, 2006.
- [Sat63] Ichirô Satake. Theory of spherical functions on reductive algebraic groups over \mathfrak{p} -adic fields. *Inst. Hautes Études Sci. Publ. Math.*, (18):5–69, 1963.
- [Tit72] J. Tits. Free subgroups in linear groups. *J. Algebra*, 20:250–270, 1972.
- [Tit87] Jacques Tits. Uniqueness and presentation of Kac-Moody groups over fields. *J. Algebra*, 105(2):542–573, 1987.